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The PARTRACK model for calculation of the spreading and deposition of drilling mud, chemicals and drill cuttings

Henrik Rye *, Mark Reed, Narve Ekrol

SINTEF Applied Chemistry, 7034 Trondheim, Norway

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Abstract

A model has been developed for the calculation of the spreading and deposition on the bottom of drilling mud and cuttings as well as the spreading of chemicals in the free water masses. The calculations are based on the 'particle' approach, combined with a near field plume model and with the possibility of applying external current fields for the horizontal advection of the particles. The model consists of a plume mode and a far-field mode. The plume mode takes into account effects from water stratification on the near-field mixing, ambient currents and geometrical configuration of the outlet. Once the plume has been trapped in the water masses, particles are free to fall out of the plume and deposit on the bottom. Downwards (or rise) velocity of the particles is dependent on size and particle density. Up to 36 different particle classes can be used. Chemicals may be represented in the model as 'particles' which are either very small or with neutral buoyancy. The far-field mode includes the downstream transport and spreading of particles and dissolved matter, once the plume mode is terminated. The model has been applied to calculate concentration fields for releases of matter into the free water masses, as well as the accumulated deposition on the bottom from an exploration drilling and a regional study of expected depositions from more than 15 years of drilling activity at 10 locations outside the western coast of Norway. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Drill cuttings; Releases to sea; Computer modelling; Dilution

Software Availability

Name of the software:	PARTRACK (Particle Tracking)
Developer:	SINTEF Applied Chemistry
Contact Address:	SINTEF Applied Chemistry, Env. Dept., 7034 Trondheim, Norway
Hardware required:	Pentium PC. Storage of 3D ocean current fields may require 1GB storage capacity
Software required:	Windows NT
Program language:	C + +
Availability:	Contact one of the authors at SINTEF Applied Chemistry, Trondheim, Norway

* Corresponding author. Tel.: + 47-73-59-13-19; fax: + 47-73-59-70-71; e-mail: henrik.rye@chem.sintef.no

1. Introduction

This paper calculates the expected areas of influence from the expected use of water based mud during exploration drilling, using the PARTRACK model operable at SINTEF Applied Chemistry. The paper also explains some of the features of the numerical model used, including the behaviour of the near-field mixing zone, the passive spreading in the marine recipient as well as the deposition of the falling particles on the sea floor. For the advective transport, a three-dimensional (3D) current field has been generated by an external hydrodynamic model.

Details of the PARTRACK model are explained in Section 2. Details of the release conditions assumed are explained in Section 3. Section 4 outlines the results from a calculation of releases from an exploration drilling at the Ormen Lange gas field recently discovered by Norsk Hydro. Also, some regional results for the accumulated depositions expected in the Haltenbanken area are shown.

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2. The PARTRACK model, the near-field and far-field zones.

2.1. General

PARTRACK is a software tool for modelling and simulating the release of drilling muds, cuttings and chemicals from offshore platforms. Produced water releases can also be simulated. Given model inputs such as ambient currents and densities, chemical and physical properties of the effluent, and details of the release scenario, PARTRACK simulates the release and spreading of the effluent within a 3D ocean grid. The simulation consists of two sequential steps:

1. Convective descent or ascent in the near-field zone
2. Passive particle transport and spreading in the far-field zone

Step 1 lasts for a few minutes or so and involves the creation of the 'mud plume'. The density difference between effluent and ambient leads to the initial convective descent of the plume (or ascent in the case of a lighter effluent such as produced water). As the plume moves vertically, it entrains ambient water. This often enables the plume to attain a density equal to that of the ambient before the plume hits the ocean bottom (or surface). This neutral buoyancy signals the end of convective movement (for the most part) and the beginning of the spreading in the far-field zone.

Particles are released from the plume in accordance with their sizes and densities (and hence sinking/rising velocities). Particles are transported via ambient currents and diffusion. At each time step, PARTRACK has an overview of all particle locations. From this data, it computes the mass distribution of the effluent along with its concentrations in both water and sediments. This data holds the most relevance for the typical environmental analyses performed by PARTRACK.

The remainder of this section describes the models used for PARTRACK's simulation phases in a little more detail.

2.2. Convective descent or ascent

In this phase, the density difference between the effluent and the ambient dominates. The jet therefore rises or sinks to a level of neutral buoyancy. During this (largely) vertical trajectory, three key physical processes are at work:

1. Entrainment of ambient fluid within the effluent plume.
2. Sinking out of effluent particles from the plume.
3. Exertion of drag forces on the plume by the ambient fluid.

The convective descent model of (Brandsma et al., 1980; Brandsma, 1994) accounts for each of these processes in computing the fluxes of mass Q, momentum M and buoyancy B. These three conservation equations are expressed with respect to s, a distance along the jet axis (i.e. the curve traced by the plume's centre as it moves out from the release point).

$$\text{Mass flux: } \frac{dQ}{ds} = E\rho_a - \sum_{i=1}^{n} s_i\rho_i \tag{1}$$

$$\text{Momentum flux: } \frac{d\vec{M}}{ds} = B\vec{j} + E\rho_a\vec{U}_a - \sum_{i=1}^{n} S_i\rho_i\vec{U} - \vec{F} \tag{2}$$

$$\text{Buoyancy flux: } \frac{dB}{ds} = E(\rho_w - \rho_a) - \sum_{i=1}^{n} s_i(\rho_w - \rho_i) \tag{3}$$

Regarding mass flux, the first term in Eq. (1) represents the entrained mass, where E is the entrainment rate (which is based on both the plume's momentum and the convective stability of the ambient fluid) and $\rho_a(z)$ is the ambient density at the current location of the plume's head. Vertical variation of temperature and salinity in the ambient water (stratification) is allowed for. The second term denotes the flux due to the sinking out of particles, where n is the number of particle classes, s_i is the volume loss due to the sinking of the $_i$th particle type, and ρ_i is the density of the $_i$th particle type.

The momentum flux in Eq. (2) consists of (a) a buoyant force, B in the vertical direction (where the $\vec{j}$ component points along the vertical y axis), (b) a momentum gain due to entrainment, where $\vec{U}_a$ denotes the 3D vector of ambient current velocities, (c) a momentum loss due to particle sinking, where $\vec{U}$ is the plume's 3D velocity vector, and (d) the drag, $\vec{F}$ resulting from the ambient fluid.

In Eq. (3), the buoyancy flux involves a component for entrainment and one for particle sinking. In both cases, ρ_w refers to the density of the carrying water in the release. For the entrainment component, the buoyancy gain is based on the difference between the medium's density and the ambient density. For the sinking component, the difference is between the medium's density and the particle density, since the sinking particle is assumed to be replaced by the plume's internal fluid.

The conservation equations are solved via a 4th order Runge–Kutta algorithm. The near field zone ends when passive diffusive and advective forces begin to dominate the plume's momentum in the calculation of horizontal spreading. In most PARTRACK simulations, this phase ends less than an hour after the release time. The remainder of the simulation is then dedicated to advective and diffusive transport of particles, as explained below.

2.3. Particle release and transport

During plume development, heavier particles tend to sink out of the plume. In the model, particles of a particular class sink out of the plume when their sinking velocities exceed the descent or ascent velocity of the plume. The sinking velocity (V_s) is calculated as a function of the diameter of the particle (d), the specific gravity of the substance (γ_s), the specific gravity of the ambient fluid (γ), gravitational acceleration (g), and the fluid kinematic viscosity (ν). A kinematic viscosity of 1.858 $\times$ 10^{-6} m^2/s for salt water is used.

As described in (CERC, 1984), the fall velocity depends upon the relationship between the Reynolds number ($V_s d/\nu$) and the buoyancy index (Bi), where:

$$Bi = [(\gamma_s/\gamma) - 1]gd^3/\nu^2 \tag{4}$$

The buoyancy index determines the appropriate equation for V_s:

$$V_s = (\gamma_s/\gamma - 1)gd^2/18\nu \; (Bi < 39) \tag{5}$$

$$V_s = [\gamma_s/\gamma - 1)g]^{0.7}d^{1.1}/6\nu^{0.4} \; (39 < Bi < 10^4) \tag{6}$$

$$V_s = [(\gamma_s/\gamma - 1)gd/0.91]^{0.5} \; (Bi > 10^4) \tag{7}$$

Given V_s, The PARTRACK model computes the release points of particles from the plume in two phases:

1. During the plume-development computations, the particles of a particular class (denoted class c) fall out of the plume when their (presumably mutual) fall velocity, (V_{sc}) exceeds the vertical plume velocity, V_p. So, a comparison of V_p to V_{sc} at each time step eventually yields a release location (S) along the plume axis for the particle class c.
2. All particles of class c are released at plume-axis location S, but at a variety of random points within a radial sector below the plume's axis.

Once the particles have left the plume, they will sink down to the bottom. Resuspension of matter located on the bottom is not included in the present model.

For dissolved matter, the particles that represents the release are generally assumed so small that they will have no descending or ascending motion relative to the fluid.

2.4. Far-field diffusion and advection processes

Once released from the plume, the motion of particles become strictly dependent upon ambient-current advection and diffusion. Thus, the 3D velocity vector ($\vec{V}$) of a particle is the sum of an advective ($\vec{V}_a$) and a random motion ($\vec{V}_r$) vector (where the three components of $\vec{V}_r$ are scaled by the horizontal and vertical diffusion coefficients):

$$\vec{V} = \vec{V}_a + \vec{V}_r \tag{8}$$

The advective vector ($\vec{V}_a$) is composed of a horizontal velocity component in two dimensions imported from an external data base. This velocity may be specified at a given point, based on current measurements at various depths in fixed positions. Alternatively, it may be originated from 3D hydrodynamic models, calculating the horizontal current component as a function of x, y, z and time.

For the vertical motion of the particle, the fall velocity of the particle is used, calculated as a function of diameter and particle density as given by Eqs. (5)–(7).

The far-field diffusion is expressed through random walk processes of the particles released from the plume, expressed through the velocity component ($\vec{V}_r$) in Eq. (8). The choices of diffusion or dispersion coefficients for the effluent are based on the following. Horizontal shears in the current field contribute to dispersion of contaminants in the modelled water column. Additional dispersion is parameterized through horizontal diffusivity parameters, K_x and K_y. For the particle based approach, the horizontal diffusivity parameters are both related to the time that has elapsed since the release of the particle according to the relation (derived from Bowden, 1983):

$$K_x = K_y = 1.17\; 10^{-6}\; t^{1.34} \tag{9}$$

which is valid for $K_{x,y}$ in m^2/s and t in seconds. In order to control the size of K_x and K_y, an upper bound is assumed for these coefficients. This is to be specified by the user, usually the upper bound is chosen between 10 and 100 m^2/s.

The vertical diffusion coefficient is specified by the user. Usually, the number is chosen between 10^{-4} m^2/s (calm conditions) and 10^{-2} m^2/s (rough weather conditions).

A particle based random walk algorithm (Reed, 1980) is used to simulate both horizontal and vertical dispersion in the water column. Particles diffuse with velocities V_i,

$$V_i = R^* \sqrt{6K_i/\Delta t ...} \tag{10}$$

where the subscript i = 1,2,3 corresponds to the horizontal and vertical directions x,y,z, K_i is associated diffusivity, Δt is the model time step, and R^* is a random variate uniformly distributed over the interval $-1.0 \leq R^* \leq 1.0$. The value of K_z is usually selected between 10^{-4} m^2/s (calm conditions) and 10^{-2} m^2/s (rough weather conditions). The values of K_x and K_y are computed from Eq. (9).

The concentrations in the water masses and on the bottom are then evaluated by averaging over the particle number located within one grid element, adding the mass associated to all particles within that element and then dividing with the element volume (or area). The far-field spreading algorithm for a passive tracer has been verified against field measurements on the Oseberg field in the North Sea. Details can be found in Rye et al. (1996).

3. Characteristics of drilling mud and cuttings

The program PARTRACK has been used to predict the deposition of the drill cuttings and mud on the sea floor as well as the concentrations of the drilling mud and chemicals in the free water masses for one exploration drilling carried out at the Ormen Lange field outside the western coast of Norway. Input data was supplied by the operator, Norsk Hydro, on the actual releases expected before drilling. These data was used in the calculations. Also, data released by Statoil have been used to illustrate the predicted deposition of drill cuttings and mud in the Haltenbanken area.

The releases are basically drilling mud and cuttings. Amounts and rates are usually specified by the operator. When such information is lacking or not complete, it is possible to make predictions based on general knowledge of the practice followed under a typical exploration drilling. In this particular case, information supplied by the operator is supported by general results obtained in a recent study carried out by the Norwegian Oil Industry Association (OLF, 1996). This study specifies amounts and rates of drilling mud and cuttings typically used on the Norwegian Continental Shelf (NCS). The study also considers environmental effects from this type of release typically expected in different areas of the NCS, including the Barents Sea region.

Norsk Hydro supplied estimates on the expected amounts of the water based mud (WBM) to be used for the three lowest sections of the well. The amounts of the different products used as well as the expected duration of drilling these sections (effective drilling time included only) are shown in Table 1.

Density of barite ($BaSO_4$) is assumed to be 4200 kg/m^3. Glycol is assumed to be the compound with the largest potential harm to the environment. The matter was modelled by PARTRACK by assuming glycol to be represented by 1 μm particles. These are so small that their sinking (or rise) velocity will be negligible. It will therefore act as a passive tracer in the model. No degradation or other decay processes are included in the model calculations.

The cuttings and the barite have both a particle structure. Their behaviour will therefore be strongly dependent on the sizes of the particles. Small-sized particles have a small ability to fall through the water column, and will thus be carried away with the currents. Saga (1994) has investigated the particle size distribution (by weight) of drilling mud and cuttings during an exploration drilling in the Barents Sea. Their data have been used in this study.

For the drilling mud, the particles are generally much finer. This also leads to lower sinking velocities. The barite will therefore generally tend to spread in the water column rather than sinking down to the bottom.

The location of the Ormen Lange drilling site was 63°32′27.5″ N and 5°21′14.7″ E.

4. Calculation results

4.1. General ambient conditions

Examples of calculation results are shown in three parts. These are:

- The deposition of drill cuttings and coarse mud on the sea bottom
- The dilution of glycol in the free water masses
- The spreading and deposition of fines (basically barite)

These three different release compounds are treated separately in the calculations, as shown in the following.

For all the calculations, currents are adapted from the hydrodynamic model SINMOD-3D, which calculates currents in the recipient as a function of x,y,z and t. A brief review of the model is given in (Rye et al., 1996). The model has been run for one year (1 June 1987–31

Table 1
Amounts of constituents of the drilling mud expected to be used for the three deepest sections of the well. Numbers in tonnes. Figures supplied by Norsk Hydro

Drilled section	Duration of drilling (days)	DFE 1501, (glycol)	Aquacol S (glycol)	Barite	Total amount of drilling mud
$17\frac{1}{2}''$	5	35.691	10.707	94.225	481.831
$12\frac{1}{4}''$	3	13.687	4.106	63.507	201.196
$8\frac{1}{2}''$	12	17.573	5.271	131.443	289.938
Sum WBM		66.950	20.085	289.164	972.965

May 1988). The model area covers the surroundings of the location to be considered. Currents are specified in a 20 km horizontal grid, with a vertical resolution of maximum 14 depths.

The model PARTRACK also needs a specification of the stratification in the water masses. The actual drilling operation is planned to take place in the summer season, where some density gradients are usually generated in the upper water masses due to the summer heating. This was accounted for in the model by specifying the vertical variation of temperature and salinity of the ambient water masses.

4.2. Results for the deposition on the sea bottom

Calculations of the deposits on the bottom are carried out by releasing a number of particles (at each time step) that corresponds to the number of particle classes selected. These were chosen according to the particle diameters for the drill cuttings and mud. The classes for the lowest diameters were merged into one group, because the diameters of these particle groups are so small that they are apparently not sinking at all (sinking velocity lower than 0.5 m/day for these classes). The particles are released jointly with the sea water, which then form a sinking plume. When the plume is diluted, the velocity of the plume will be reduced. When the velocity of the plume becomes lower than the sinking velocity of the particle class in question, the particles for that class will leave the plume (as explained in Section 2) and sink down to the bottom. The path of the plume will therefore be a sum of the downwards motion of the particle combined with the horizontal current velocity of the ambient water experienced by the particle on its way down to the bottom.

The deposition on the bottom becomes therefore a result of the particle classes assumed in the calculations and the time and space varying currents assumed during the simulation period.

Fig. 1 shows an illustration of the calculation technique used. The figure shows different particles with colour codes for the various particle classes. The particles are spread in the water column, dependent on their size, weight, ambient currents and turbulence in the seawater. Some of the particles are also located on the sea floor (basically the red ones).

Fig. 2 shows the results from the calculation of the deposition of the drill cuttings on the sea floor for the four groups with the largest particle sizes. These are the ones which also have the largest sinking velocities (larger than 1 cm/s or 1 km/day). They will therefore deposit closest to the drilling site. The depth of the location is about 900 m, so they will essentially deposit within the first day after the have been released. The deposition is basically located towards NE, which is the dominant direction of the currents in the area. For the interpretation of the colour code in terms of thicknesses of the bottom layers, a weight equal to 2–4 g/m^2 corresponds to a layer thickness of about 1 μm, which will represent an average thickness that is lower than the particle diameters for these classes. Maximum deposits are calculated to about 0.3 kg/m^2, which corresponds to about 0.075–0.150 mm thickness.

Figures for finer materials than the four coarsest groups are not shown, because these will generally be transported a long distance before they deposit. They will therefore show a large spread and a corresponding low thickness of the layer on the sea floor. Concentrations on the bottom are calculated to be lower than 1 g/m^2 (or thickness lower than 0.5 μm) for the remaining classes.

Attempts to verify calculations of deposits on the sea bottom caused by exploratory drilling have been made by Lie et al. (1994). During an exploratory drilling in the Barents sea, sediment traps were deployed at distances of order 500–1000 m from the drilling site. Their measurement results indicated layer thickness lower than 1 μm resulting from the drilling of one exploratory well, which is lower that what was found downstream in these calculations. The reason for the discrepancy may be that the sediment traps were not located sufficiently in the downstream direction during the drilling period. The main bulk of the cuttings may therefore have deposited elsewhere.

4.3. Concentration of glycol in the water masses

For the calculation of the glycol concentrations, it is not necessary to simulate the whole drilling period, but rather focus on the drilling section where the release rate of glycol is expected to be largest. This will be the case for the 17.5″ section, where 46.4 tonnes of glycol are planned to be released during a time span of 5 days (see Table 1). The release of glycol is represented by particles with diameter equal to 1 μm in the PARTRACK model. These particles will be so small that they will have a negligible sinking velocity.

Fig. 3 shows the calculated near-field concentrations of glycol. The depth of trapping of the underwater plume is calculated to be close to 25 m. For the stratification, an expected temperature and salinity profile for the area in the month of September was used. The calculations show that maximum concentrations in the interval 1–10 g/m^3 can be expected within a distance of 2 km from the release site. Within a distance of 1 km from the release site, the concentration level is expected to be at maximum 3–10 g/m^3.

Table 2 shows the fate of the various compounds in the release after a simulation time of 35 days (the complete exploration drilling period). Note that while the glycol is completely contained within the free water masses and that the drill cuttings are basically deposited

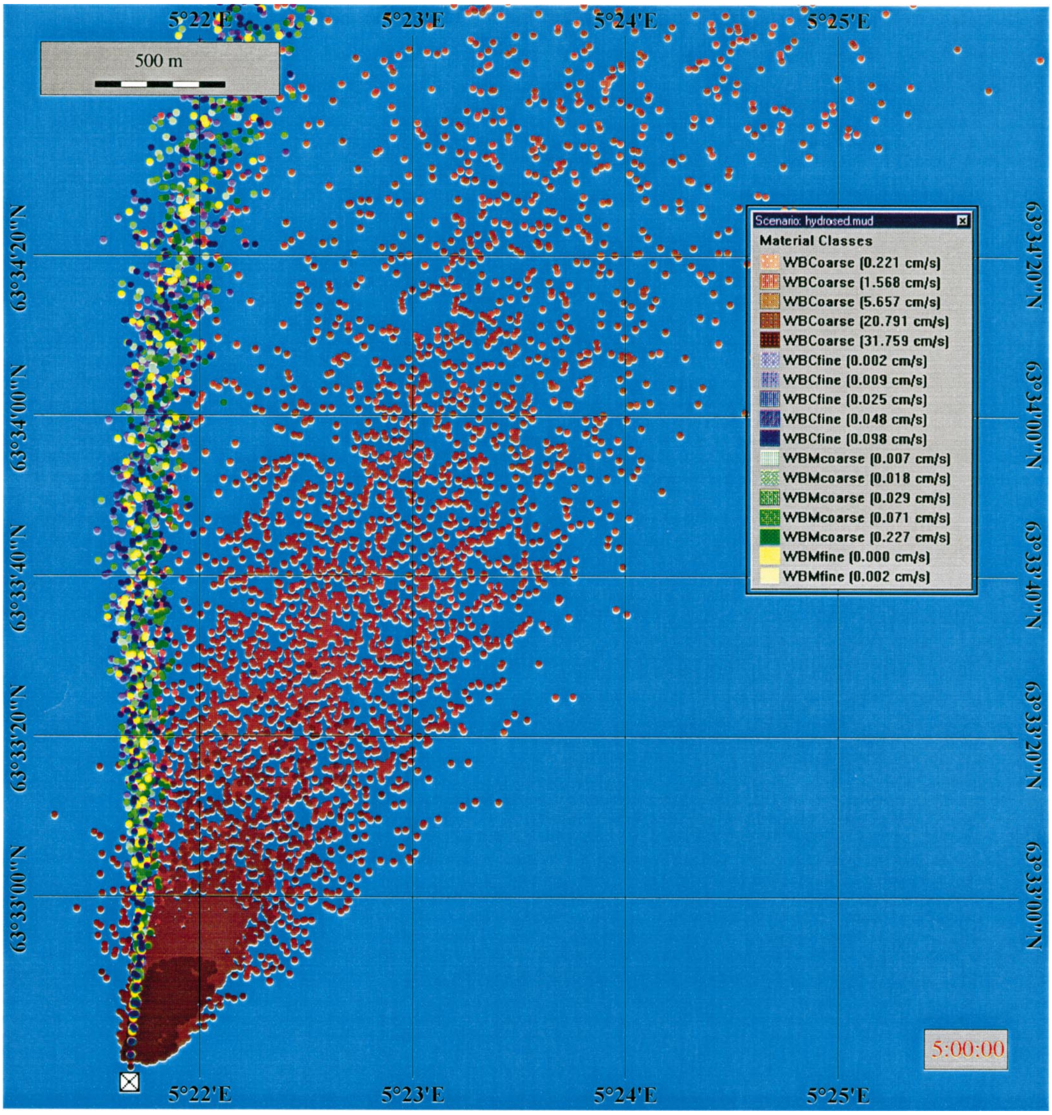

Fig. 1. Particle cloud for the Ormen Lange field after 5 days of drilling. Red particles: drill cuttings, coarse. Blue particles: drill cuttings, fine. Green particles: drilling mud (barite), coarse. Yellow particles: drilling mud (barite), fine. The red particles (basically to the right) have deposited on the sea bottom, while the other coloured particles (basically to the left) are still in suspension in the water column.

on the sea bottom, the drilling mud is still suspended in the free water masses to a large extent (66%). The reason for this is the fine particle nature of the barite, with sinking times that extend beyond the simulation period.

PNEC (Predicted No Effect Concentration) levels for glycol are expected to be of the order of 0.3 mg/l or 0.3 g/m^3, SINTEF (1998). This level is expected to be surpassed outside the area shown in Fig. 3. Fig. 4 shows an example of calculated concentration levels on a larger geographical scale, where the concentration levels are generally lower than 0.3 mg/l. Fig. 4 shows the spreading of glycol in the water masses after five days of release with continuous drilling.

4.4. *Deposition of drill cuttings and mud on a regional scale*

The deposits of the fines will generally take place on a larger geographical scale. The PARTRACK model is able to aggregate releases from more than one drilling period and also from more than one drilling site. This chapter shows an example of calculation of the deposits of the finer parts of the drill cuttings as well as the drilling mud on a larger geographical scale from an anticipated drilling program for 10 different locations over a time span of more than 15 years for the Haltenbanken area (SINTEF, 1997). The total amount of particulate matter in drill cuttings and mud was estimated to be in

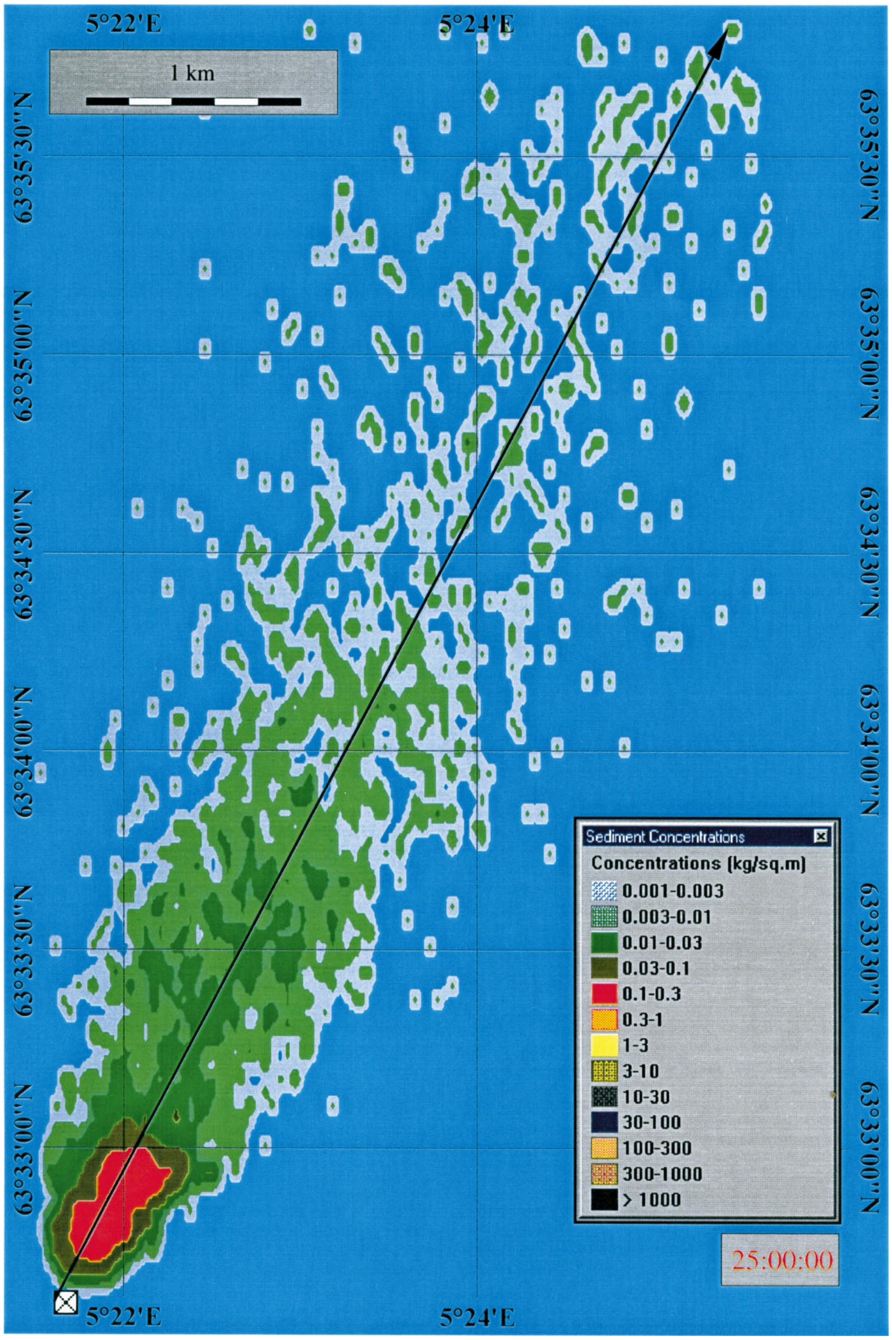

Fig. 2. Concentration of the four largest particle classes on the sea floor after the termination of the simulation (25 days). The release for one exploration drilling has been condensed into 5 days of effective and continuous drilling, although the actual drilling time will be considerably longer than this (see Table 1).

excess of 500 000 tonnes in total. The amounts of drill cuttings and mud (particulate) per well were assumed to be 2100 tonnes in this study, mainly based on information found in OLF (1996). These amounts are somewhat larger per well than for the exploratory well considered in Section 3. Total number of wells for the Haltenbanken study is about 240 (production wells as well as exploratory wells).

Fig. 5 shows the results from the calculations. The release was allowed in the program to run continuously over a longer time span, until the total amounts were released. Although the actual release will, in reality, be spread in time over many years, the simulations were carried out within the time span available through the one year current database. By extending the simulation time over some months, the variability of the ambient conditions expected through the years was assumed to be taken care of by extending the simulation over a

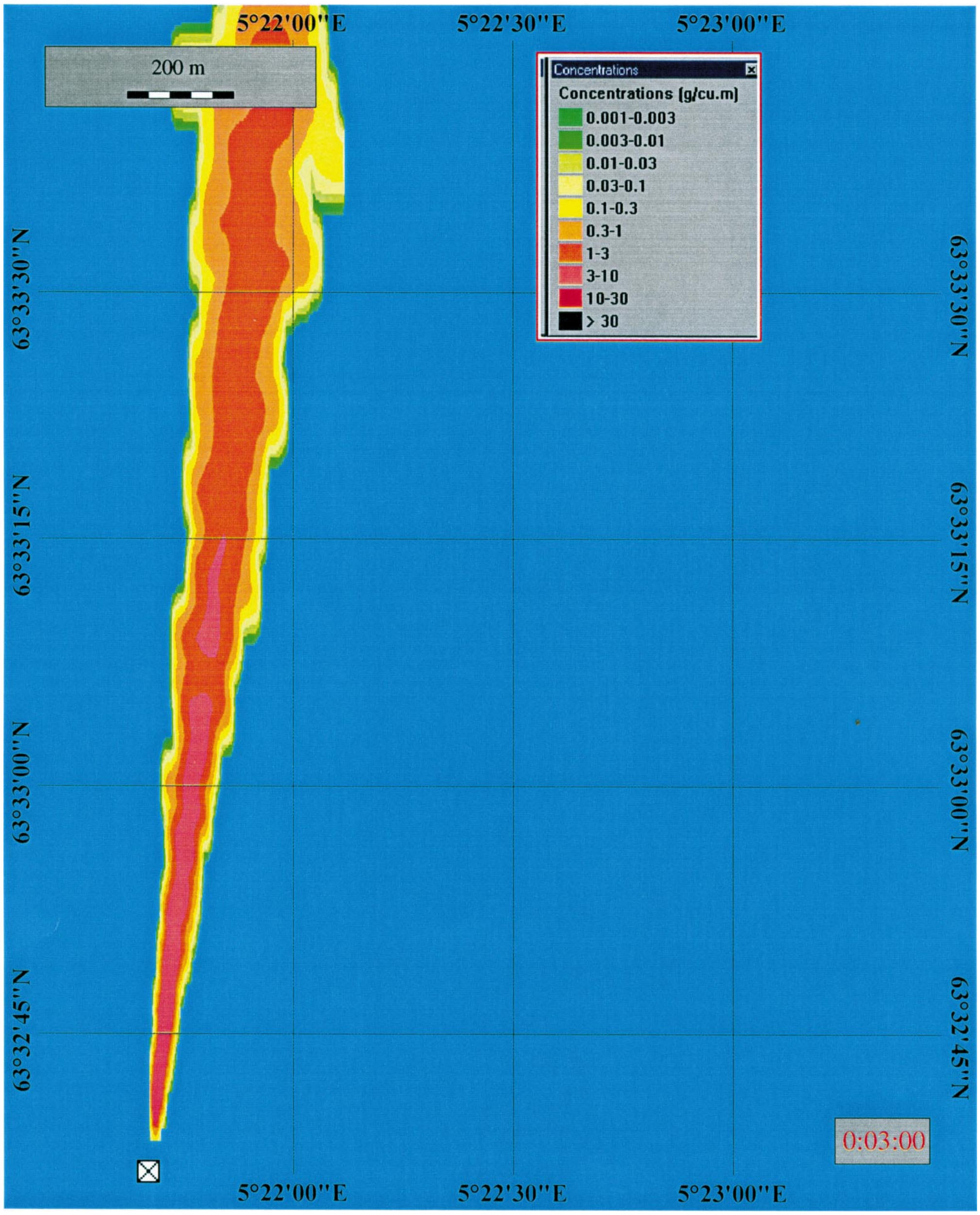

Fig. 3. Concentration levels of glycol in the near field area. Depth of trapping is calculated to be about 25 m.

Table 2
Mass balance between matter contained in the free water masses and matter deposited on the sea bottom. Simulation time 35 days

	Water	Bottom	SUM
Drilling mud	66	34	100
Glycol	100	0	100
Drill cuttings	23	77	100
Sum	56	44	100

longer time span (but still within the 1 year data series available for the currents).

Fig. 5 shows the area of the deposits to be considerably extended, compared to the results shown for one single exploratory drilling. The reason for this is that the total number of wells drilled has increased considerably. For some of the fields in the Haltenbanken area, more than 40 wells are planned. The calculations show that for some of the fields planned, some overlap of the deposits from the different fields is expected. The maximum concentrations in the overlap areas are of the order of 30–100 g/m^3, which represent a layer thickness of approx. 10–40 μm. The distance from the source in these overlap areas are large (~ 10 km or more), which

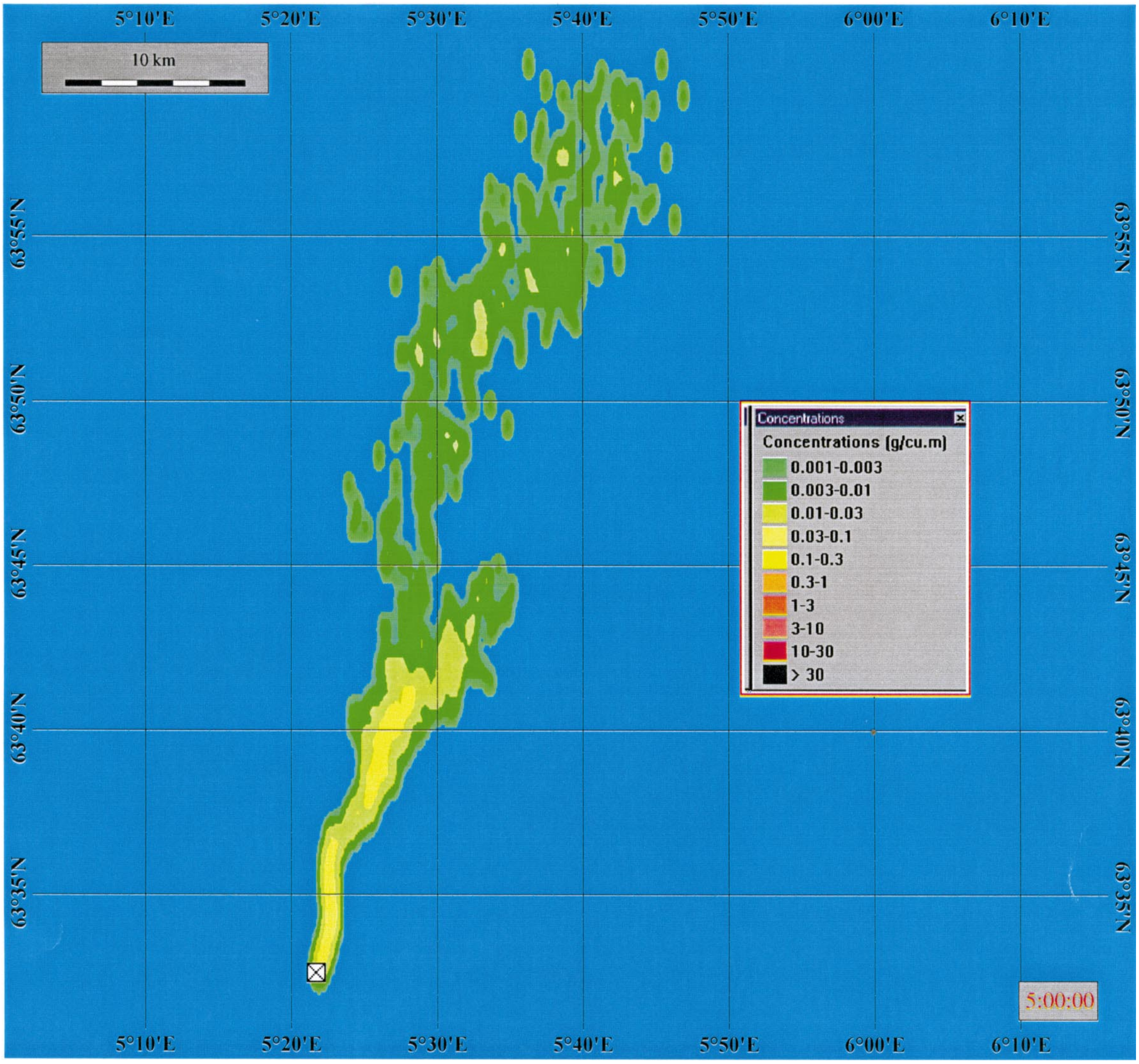

Fig. 4. The spreading of glycol in the far field zone. The PNEC level for glycol is assumed to be of order 0.3 g/m^3.

means that the size of the particles that sediments here will be smaller than the results based on the particle classes shown in Figs. 1 and 2.

In Lie et al. (1994), a criterion for resuspension of deposited matter on the sea bottom is formulated in terms of the sinking velocity of a particle. If the sinking velocity of the particle is lower than 10^{-3} m/s, the particle is expected to be brought into resuspension. This number is probably dependent on the sizes of the current velocities close to the bottom. A sinking velocity equal to 10^{-3} m/s corresponds to a particle size diameter equal to 35 μm (barite) or 50 μm (drill cuttings). These particle sizes will therefore deposit after a time span of order 10^6 s in areas of 1000 m depths (= 1000 m depth divided by 10^{-3} m/s), which correspond to approx. 10 days. The particles deposited in the most remote areas must therefore expect to resuspend after some time.

Also note that local maxima appear in Fig. 5, outside any of the sources of the releases. This is believed to be caused by particles that move into more shallow water areas. If these particles are located relatively deep, they will deposit (in the model) when the depth in the model is more shallow than the particle depth. These local maxima in the model may therefore be an artifact caused by the design of the model. On the other hand, local maxima are expected to occur within areas with calm current conditions where the particles will be allowed to deposit. This effect is taken care of by the model due to the time- and space-varying current conditions applied by the model.

5. Conclusions

The PARTRACK model have been shown to be a practical tool to predict depositions on the sea bottom as well as concentration in the free water masses from releases of chemicals, drill cuttings and mud from

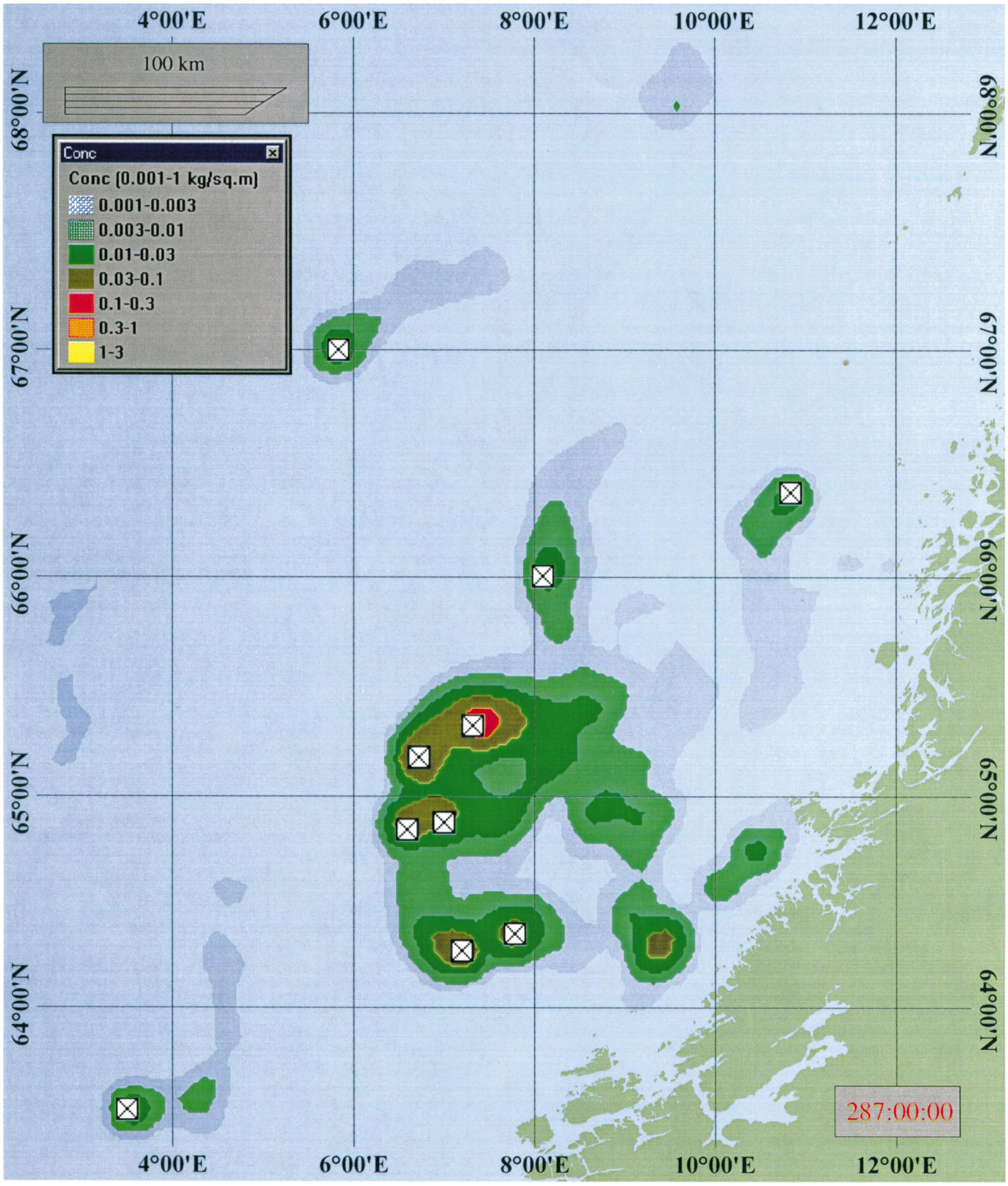

Fig. 5. Total accumulated drill cuttings and mud on the sea floor caused by releases from 10 different sites in the Haltenbanken area during a time span of more than 15 years. Reproduced from SINTEF (1997).

exploratory and production drilling performed by the oil and gas industry offshore.

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